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Research article

Dynamic forage-livestock balance analysis in alpine grasslands on the Northern Tibetan Plateau

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ABSTRACT

Forage-livestock balance is important for sustainable management of alpine grasslands under global change, but the robustness of diverse algorithms for assessing forage-livestock balance is still unclear. This study compiled long-term (2009–2014) field observations of aboveground biomass (AGB). Using climate and remote sensing data, we evaluated the inter-annual dynamics of the forage-livestock balance on the Northern Tibetan Plateau (NTP). Here, we assumed that AGB dynamics in fenced grasslands (AGB_F) is only driven by climate change; whereas AGB dynamics in open grasslands grazed by livestock (AGB_G) is driven by a combination of climate change and human activities. Thus, human-induced change in AGB (AGB_H) could be estimated via the difference between AGB_F and AGB_G. Furthermore, differences in the temporal trends between AGB_F and AGB_H could indicate the state of forage-livestock balance, overgrazed or not, in alpine grasslands. Our results showed that the overall status of the forage-livestock balance from 2000 to 2006 was overgrazed owing to poor climatic conditions. Ecological projects and economic policies for alpine grassland conservation had not been implemented at that time, which also resulted in local overgrazing. From 2006 to 2014, the alpine grasslands in some areas were in a less-grazed state. We suggest that the livestock number could potentially increase in northern NTP and should be reduced or strictly controlled to maintain the balance between livestock and forage in the southern and southeast areas. In conclusion, the results of this study suggest that the evaluation of the forage-livestock balance in the NTP should include the local climatic conditions and make better use of grassland resources while ensuring ecological security.

1. Introduction

Grassland ecosystems are widely distributed globally and are fundamental for environmental protection, economic development, and human welfare (Ebrahimi et al., 2016; Li et al., 2017; Liu et al., 2018; Ryals et al., 2015). But, grasslands have been degraded owing to climate change and human activities in the past decades (Cai et al., 2015; Gang et al., 2014). Global climate change including warming and precipitation changes affect the dynamics of ecosystem function and service over time in grasslands (Piao et al., 2012; Qin et al., 2013; Wang et al., 2012). Compared with climate change, human disturbances are more direct and rapid in driving grassland degeneration (Li et al., 2009; Luo et al., 2018). Scientists have found that a moderate stocking rate is beneficial to maintain grassland health, but overgrazing might decrease aboveground biomass (AGB) and net primary productivity (NPP), ultimately resulting in grassland degradation (Lu et al., 2015, 2017; Luo et al., 2012; Mcnaughton, 1983; Yan and Lu, 2015). Therefore, assessing the balance between forage production and livestock consumption (forage-livestock balance) is essential for reasonable and sustainable grassland management.

Maintaining the forage-livestock balance is key for preventing grassland degradation. To date, methods for assessing the forage-livestock balance remain controversial (Galt and Holechek, 2000). As the basis for calculating the stock carrying capacity, forage production should be accurately estimated. Field observation is the most effective method for forage estimation; however, it is laborious and time-consuming and its predictively is limited at large spatial scales (Fan et al., 2007; Jmo et al., 2002). Model simulation, which is universal and

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predictable, is an effective method to estimate biomass (Gao et al., 2009; Melillo et al., 1993; Piao et al., 2006a; Potter et al., 1993). In such a simulation, scientists always first establish an empirical model between the remote-sensing vegetation index and field-measured AGB, and then apply it to estimate forage production at a broader scale (Jia et al., 2016; Jin et al., 2014; Ullah et al., 2012). For example, the normalized difference vegetation index (NDVI), a sufficiently stable vegetation parameter that reflects seasonal and inter-annual changes in plant growth and activity, is widely used for AGB estimation in regional and global grassland (An et al., 2013; Liang et al., 2016; Meng et al., 2017; Zhang et al., 2015). When assessing the forage-livestock balance in grassland, domestic herbivores of different types, sizes, and ages are usually converted into "standard livestock." In China, a standardized sheep unit (SU) is usually used and the daily forage requirement per standardized sheep unit is 1.8 kg, (NY/T635-2015). Forage requirements of livestock units represent only the nutritional needs of a livestock unit, but livestock intake reflects the interaction between livestock and grassland environmental conditions. Therefore, standardized daily forage requirement does not indicate the feed intake proportional to feed requirement of livestock units (Currie, 1986; Scarnecchia, 1985). The traditional assessment of forage-livestock relations is based on the theory of equilibrium (Holechek, 1999), ignoring the livestock's own adaptation to grassland productivity and the effects of abiotic factors. Therefore, finding a new way to dynamically evaluate the forage-livestock balance is necessary for rational utilization of grassland resources in the context of climate change.

In China, alpine grasslands are mainly distributed on the Qinghai-Tibet Plateau (QTP), where natural alpine grasslands account for about 85% of the total land area (Dong et al., 2010). The Tibetan alpine grasslands are fragile and vulnerable to climate change and human activities (Chen et al., 2013; Zhang et al., 2007). Nearly half of the alpine grasslands on the QTP are degraded owing to climate change and unsustainable human activities; e.g., excessive livestock grazing (Dong et al., 2010; Harris, 2010). Overgrazing has been considered the main cause of grassland degradation, and therefore, grazing exclusion by fencing has been widely recommended to restore degraded grasslands (Fan et al., 2013; Wu et al., 2017). Furthermore, Alpine grasslands on the QTP are also greatly affected by climatic conditions (Gao et al., 2009; Jiang et al., 2017). Climate warming and drying trends of the QTP has become more serious in the past 30 years, which has also made the alpine grassland more vulnerable to degradation by human activities (Chen et al., 2014; Li et al., 2018). Ecological projects and eco-compensation policies have been implemented for restoration of degraded grasslands and conservation of health pastures on the Tibetan Plateau (Yu et al., 2016), however, the degradation caused by overgrazing is still evident somewhere (Li et al., 2013; Liu et al., 2017). To ensure grassland ecological security and achieve sustainable development, it is critical to assess the balance of forage and livestock on the plateau. Based on the equilibrium theory, the traditional method for assessing the forage-livestock balance advocates a conservative grazing policy, but may not fully use the forage produced in wet years (Holechek, 1999; Workman, 1986). Therefore, a dynamic assessment of the forage-livestock balance is needed to better use the forage resources in such alpine grasslands.

In this study, we used remote sensing data and long-term field data to evaluate the status of the forage-livestock balance. The main objectives were to (1) use NDVI and climate data to establish relationships with AGB, distinguish and quantify the effects of climate change and human activities on the AGB of the alpine grassland in the Northern Tibetan Plateau (NTP); (2) evaluate the forage-livestock balance using a dynamic method, and determine the reasonable spatio-temporal changes in human-induced AGB (AGB_H) and livestock number; (3) determine the main driving forces of AGB change induced by livestock grazing (AGB_G) by comparing the absolute slopes of AGB_H with that of the AGB in fenced grasslands (AGB_F); and (4) divide the potentials areas of the alpine grassland in the NTP suitable for grazing from those vulnerable to grazing, to provide a reference for future livestock management.

2. Data and methods

2.1. Data

The NTP, known locally as the "Changtang," is located in the northwestern hinterland of the Qinghai-Tibet Plateau and covers an area of about $5.95 \times 10^5\,km^2$. In the present study, our team set up a long-term transect platform in spring 2009, which crosses the alpine meadow, steppe, and desert zones from East to West on the NTP. During the field surveys each summer, alpine grassland vegetation in a flat terrain was selected along the average interval of transects from 50 to 70 km along with this long-term transect platform. At each site, we had one pair of grazing vs. fencing plots. At each plot, five quadrats of 1 m × 1 m were laid out, at an average interval of 20 m along a random sampling line for AGB harvest (Wu et al., 2012). Field surveys were conducted in August each year, when most plants are in the flowering or fruiting periods and have reached their maximum coverage, and thus, the peak AGB can be considered as a proxy for productivity. During 2009–2014, we surveyed a total of 247 grassland communities to establish a model between measured AGB and remote sensing vegetation index.

The moderate-resolution imaging spectroradiometer (MODIS) NDVI products (MOD13A3) for the study area during the period from 2000 to 2014 were obtained from the National Aeronautics and Space Administration agency (National Aeronautics and Space Administration (NASA), 2017), which were in one-month time interval and 1-km spatial resolution. The annual $NDVI_{max}$ was calculated using the maximum value composite, which is widely used to estimate the annual maximum biomass in grasslands (Holben, 1986). To further eliminate the effects of nudation and vegetation sparse areas, the areas with $NDVI_{max} < 0.1$ were not included in this study (Higginbottom and Symeonakis, 2014; Piao et al., 2006b).

Daily records of average temperature and total precipitation of the plant-growing season (May to September) from 2000 to 2014 were downloaded from China Meteorological Data Service Center. Daily meteorological records were recalculated into the spatiotemporal resolutions of the NDVI data using ANUSPLIN 4.3 (Hutchinson and Xu, 2004). The quality of the grid climate surface has been shown to have a very high correlation with observed records (Tao et al., 2015). We calculated growing season average temperature (GSMT) and growing season total precipitation (GSP) annually from May to September for further analysis.

The number of livestock was acquired from the yearly statistical book, which provides county-level statistics. According to the convention, different animals are converted into SU, one sheep or one goat is equal to one SU, and other large livestock such as cattle and horses are equal to four SU (Fan et al., 2010).

2.2. Methods

Here, we hypothesize that AGB_F is driven only by climate variables at the fenced (grazing-excluded) pastures while AGB_G is the residual biomass under the combining influences of climate and livestock grazing. Thus, the difference between AGB_F and AGB_G can be used to quantify the human-induced change (mainly owing to livestock grazing) in AGB, noted as AGB_H (eqn. (1)).

$$AGB_H = AGB_F - AGB_G \quad (1)$$

According to the geographical coordinates of sampling points inside the fences, we extracted the corresponding GSP and GSMT data to establish the relationship between climate factors and AGB_F (eqn. (2), $R^2 = 0.63$, $P < 0.0001$). Similarly, the coordinates of sampling points outside the fences were used to extract the corresponding $NDVI_{max}$. The

relationship between the measured AGB_G and $NDVI_{max}$ was established (eqn. (3), $R^2 = 0.67$, $P < 0.0001$). Finally, the three models of eqns. (1)–(3) were applied to estimate the AGB of the alpine grasslands overall NTP.

$$AGB_F = \exp(0.0055 * GSP + 0.0438 * GSMT - 0.0001 * GSP * GSMT + 1.9603) \quad (2)$$

$$AGB_G = 33.016 \times \ln(NDVI_{max}) + 81.702 \quad (3)$$

Linear regression is widely used in the trend analysis of vegetation changes (Fensholt et al., 2009). Here, time is an independent variable and AGB is a dependent variable (eqn. (4)).

$$\text{slope} = \frac{n \times \sum_{i=1}^{n} i \times AGB_i - \sum_{i=1}^{n} i \sum_{i=1}^{n} AGB_i}{n \times \sum_{i=1}^{n} i^2 - (\sum_{i=1}^{n} i)^2} \quad (4)$$

where n is the number of study years, i is the ordinal number of the year, and AGB_i is the AGB value corresponding to year i.

In this study, we evaluated the forage-livestock balance by assessing the yearly changes in AGB caused by climate change and consumed by livestock. We hypothesized that the grasslands grazed by livestock is in a stable status if there is no difference in the trends of between AGB_F and AGB_H. It also means that forage production and livestock consumption are in equilibrium and the stocking rate here is sustainable. Based on $sAGB_F$ and $sAGB_H$, it is possible to calculate the amount of AGB and the increase or decrease in the number of livestock to reach the equilibrium between forage production and livestock capacity at the county level in entire NTP.

$$AGB_T = \sum_{i=1}^{n} (sAGB_F - sAGB_H) \times A \quad (5)$$

$$C_T = \frac{AGB_T}{R \times D} \quad (6)$$

Where AGB_T is the total AGB_H (g) that needs to be increased or decreased in the current year, n is the number of grid pixels, i is the ordinal number of pixels, A is the area of pixels (m^2), $sAGB_F$ and $sAGB_H$ are the absolute slope value for AGB_F and AGB_H change trend (g/m^2), C_T is the amount of livestock required to increase or decrease in the current year (SU), R is the daily feed requirement per sheep unit in that year (g/d), and D is the number of days of grazing (d).

Through the slope of AGB_G, we can determine the change of the actual residual grassland AGB. By comparing the absolute slope values of AGB_F and AGB_H, we can identify the main driving factors of AGB_G changes in grasslands over the past years to improve the rationality of grassland management (Table 1).

3. Results

3.1. Spatial-temporal change of AGB

From 2000 to 2014, the values of AGB_F and AGB_H fluctuated significantly, with the lowest value appearing in 2006 and highest value appearing in 2008 (Fig. 1). The inter-annual difference in AGB_G values was small, with the lowest and highest values appearing in 2007 and

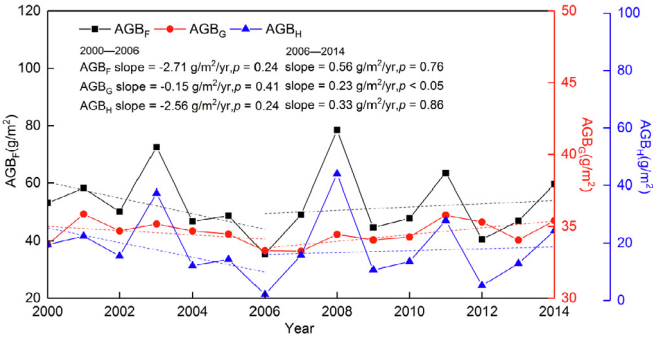
AGB_F
AGB_G
AGB_H
2000—2006
2006—2014
AGB_F slope = -2.71 g/m²/yr,p = 0.24 slope = 0.56 g/m²/yr,p = 0.76
AGB_G slope = -0.15 g/m²/yr,p = 0.41 slope = 0.23 g/m²/yr,p < 0.05
AGB_H slope = -2.56 g/m²/yr,p = 0.24 slope = 0.33 g/m²/yr,p = 0.86
AGB_F(g/m²)
AGB_G(g/m²)
AGB_H(g/m²)
Year

Fig. 1. Inter-annual variation of aboveground biomass (AGB) in alpine grassland on the Northern Tibetan Plateau. AGB_F, AGB_G, and AGB_H are the aboveground biomass in the fenced grasslands, in the open grasslands, and induced by human, respectively.

2001, respectively. AGB showed two different temporal trends between two sub-periods with 2006 as the cut-off point. For example, AGB_F, AGB_H, and AGB_G showed decreasing trends during the first sub-period before 2006. During the second sub-period after 2006 AGB_F, AGB_H, and AGB_G showed increasing trends, in which AGB_G increased significantly ($p < 0.05$), but the inter-annual fluctuations of AGB_F and AGB_H became larger. The absolute slope values of AGB_F in these two periods were always greater than AGB_H.

At the spatial scale, the regions where AGB_F significantly decreased during 2000–2006 were mainly distributed in the southern fringe of the NTP, but there was no area where AGB_F significantly increased (Fig. 2A). In 2006–2014, the areas where AGB_F significantly increased were mainly in the southeastern NTP, and there was no area where AGB_F significantly decreased (Fig. 2B). AGB_H showed the same spatial pattern of trends to AGB_F at the pixel scale. From 2000 to 2006, the areas with significant decreases in AGB_H were mainly distributed in the northern and southern fringes of the NTP. The area with significant increases in AGB_H were scattered in the western and central NTP (Fig. 2E). The regions where AGB_H decreased significantly between 2006 and 2014 were mainly in the central and southwestern NTP, and the regions where AGB_H significantly increased occurred mainly in southeastern NTP (Fig. 2F). During 2000–2006, AGB_G showed a decreasing trend in most parts of the NTP, especially in the southwestern, central, and southeastern areas. Significant increasing trends for AGB_G were found in the northern and southern fringe regions (Fig. 2C). During 2006–2014, AGB_G increased in most parts of the NTP, especially in the western and southern regions. The areas with significant decreases in AGB_G were sporadically distributed in the central part (Fig. 2D). From latitudinal variations, AGB_F and AGB_G increased in higher latitude regions, and decreased in lower latitude regions (Fig. 2G). AGB_H showed an increasing trend in the regions between 32°N and 35°N , and decreasing trend in other regions. From longitudinal variations, AGB_F, AGB_G and AGB_H fluctuated less in the regions between 82°E and 90°E (Fig. 2H). In regions with smaller longitude, AGB_G showed an increasing trend and AGB_H showed a decreasing trend. In regions with larger longitude, AGB_F and AGB_H showed a decreasing

Table 1
Causes of and methods of evaluating the aboveground biomass in the open grasslands (AGB_G) changes.

Method (comparing absolute slope)	Cause of AGB_G change
$sAGB_G = 0$, $\|sAGB_F\| = \|sAGB_H\|$	AGB_G has no change (NC)
$sAGB_G > 0$, $\|sAGB_F\| < \|sAGB_H\|$	AGB_G increase due to human activities (IHA)
$sAGB_G > 0$, $\|sAGB_F\| > \|sAGB_H\|$	AGB_G increase due to climate change (ICC)
$sAGB_G < 0$, $\|sAGB_F\| < \|sAGB_H\|$	AGB_G decrease due to human activities (DHA)
$sAGB_G < 0$, $\|sAGB_F\| > \|sAGB_H\|$	AGB_G decrease due to climate change (DCC)

$sAGB_G$, $sAGB_F$, and $sAGB_H$ are the slope value for the aboveground biomass in the open grasslands (AGB_G), in the fenced grasslands (AGB_F), and induced by human (AGB_H) change trend.

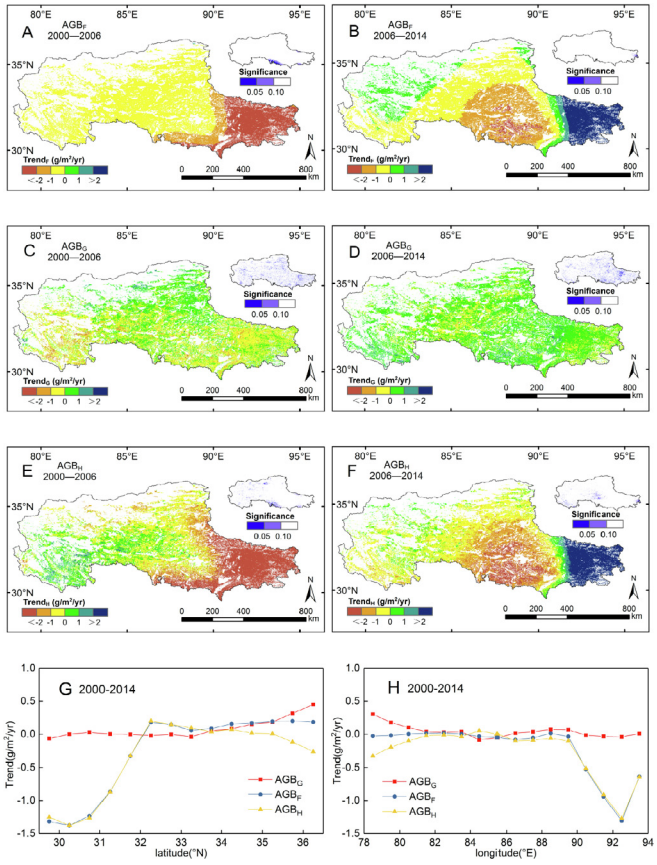

Fig. 2. Spatial distributions of aboveground biomass (AGB) trends in alpine grassland on the Northern Tibetan Plateau. (A), (C) and (E) are the spatial distribution trend of the aboveground biomass in the fenced grasslands (AGB_F), in the open grasslands (AGB_G), and induced by human (AGB_H), respectively, for the first sub-period of 2000–2006. (B), (D) and (F) are the spatial distribution trend of AGB_F, AGB_G and AGB_H, respectively, for the second sub-period of 2006–2014. The inset maps show the significant AGB trends in dark blue ($p < 0.05$) and light blue ($p < 0.1$). (G) and (H) are the latitudinal and longitudinal profile of AGB trends from 2000 to 2014. The average values of AGB trends in (G) and (H) were extracted according to the longitude interval of 1° and the latitude interval of 0.5°.

trend.

3.2. Dynamic assessment of forage-livestock balance in the NTP

In the present study, we assume that when human-induced AGB changes coincide with climate-driven AGB changes, alpine grasslands on the NTP are in a state of forage-livestock balance. In Fig. 3, green indicates that AGB_H and livestock number that could be supported in addition during that year. There were six years in surplus, of which the surplus of grassland was the highest in 2001, AGB_H could increase by 2.12 g/m^2, and the number of livestock could be supported in addition by 75.71 × 10^4 sheep units, accounting for 4.16% of the actual number of livestock in that year. Red indicates that AGB_H and livestock number that was in excess during that year. There were eight years of overgrazing, of which grasslands were the most overgrazed in 2013, the AGB_H needed to be decreased by 1.25 g/m^2, and the number of livestock was in excess by 44.67 × 10^4 sheep units, accounting for 2.42% of the actual number of livestock in that year. During the first sub-period before 2006, grasslands on the NTP were overgrazed, and it was necessary to reduce the number of livestock of 15.46 × 10^4 sheep units. Grasslands on the NTP were surplus during the second sub-period after 2006, and 74.39 × 10^4 sheep units could be supported in addition. Overall, between 2000 and 2014, there was a surplus in the grasslands

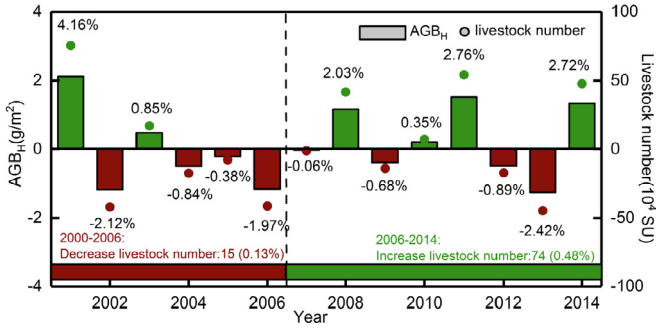

Fig. 3. Number of human-induced aboveground biomass (AGB_H) and livestock that should be increased or decreased each year. Note: The bars indicate the AGB_H needed to increase or decrease in order to reach the forage-livestock balance. The point indicates the number of livestock that need to be increased or decreased in order to reach the forage-livestock balance.

of the NTP, which could be supported in addition by 58.93 × 10^4 sheep units.

By calculating the sum of the differences between $sAGB_F$ and $sAGB_H$, we can determine the spatial distribution of AGB_H that should be increased or decreased (Fig. 4). When the AGB_H value is positive, grasslands are surplus and AGB_H can be supported in addition appropriately. When the AGB_H value is negative, the grasslands are overgrazed and AGB_H was in excess during that year. During the first sub-period before 2006 (Fig. 4A and B), the AGB_H was in excess in the NTP southwestern and southeastern regions, accounting for 57.95% of the total area. The regions that AGB_H could be supported in addition were mainly distributed in the northern and central NTP, accounting for 42.05% of the total area. During the second sub-period after 2006 (Fig. 4C and D), the AGB_H could be supported in addition in most parts of the NTP, accounting for 72.15% of the total area. The AGB_H excess was mainly distributed in the central and southeastern NTP, only

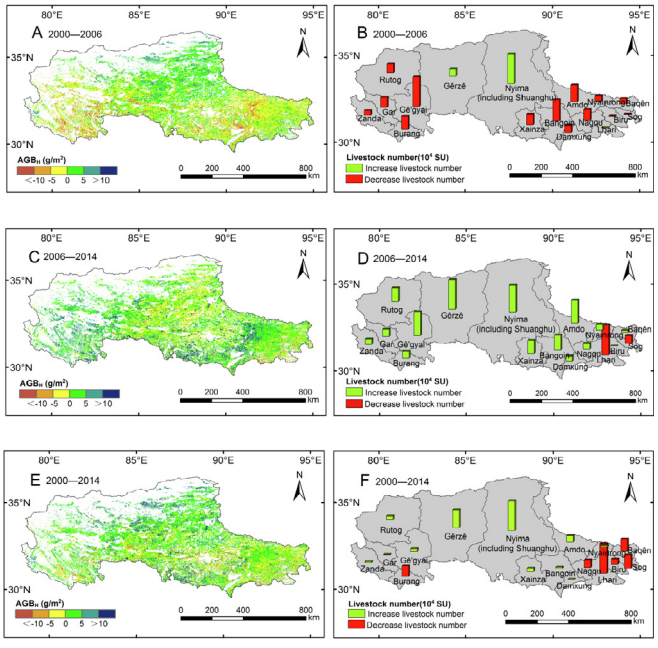

Fig. 4. Spatial distribution of human-induced aboveground biomass (AGB_H) and livestock numbers that should be increased or decreased on the Northern Tibetan Plateau. (A) and (B) are the spatial distribution of AGB_H and livestock numbers that should be increased or decreased for the first sub-period of 2000–2006. (C) and (D) are the spatial distribution of AGB_H and livestock numbers that should be increased or decreased for the second sub-period of 2006–2014. (E) and (F) are the spatial distribution of AGB_H and livestock numbers that should be increased or decreased between 2000 and 2014.

accounting for 27.85% of the total area. On the whole (Fig. 4E and F), the AGB_H could be supported in addition in the central and northwestern NTP, accounting for 64.55% of the total area. The AGB_H excess was mainly distributed in the southwestern and southeastern regions, accounting for 35.45% of the total area. On this basis, we could scientifically arrange the grazing activities in NTP and make rational use of grassland resources.

The numbers of livestock that need to be increased or decreased could be determined to estimate the total number of livestock that need to be adjusted in each county (Fig. 4C and D). Between 2000 and 2006, grasslands in 14 counties were overgrazed, mainly in the southwestern and southeastern NTP. Among them, overgrazing was relatively serious in Gê'gyai, Bangoin, and Amdo. The three counties of Gêrzê, Nyima (including Shuanghu), and Lhari were not overgrazed and the grasslands had surpluses. These counties were mainly located in the central region. Among them, Nyima (including Shuanghu) could increase the maximum number of livestock. Between 2006 and 2014, grasslands in 15 counties were not overgrazed and the grasslands had surpluses. Only Lhari and Sog counties, both of which locate in southeastern NTP, were overgrazed. Lhari changed from the grassland surplus in the first sub-period to overgrazing in this sub-period. Sog was overgrazed in both sub-periods and was more severely overgrazed in the second sub-period. These indicated that the excessive use of grassland by human activities in these two counties had been intensified. From 2000 to 2014, grasslands in six counties were overgrazed, distributed in the southwestern and southeastern of the NTP. Overgrazing was relatively serious in Lhari and the number of livestock should be appropriately reduced in the future. Grasslands were surplus in 11 counties. Among them, Nyima (including Shuanghu) could increase the maximum number of livestock and were projected to have the most abundant grassland resources in the future.

3.3. Causes for the AGB change of natural grasslands (AGB_G)

Between 2000 and 2014, there were six years of $sAGB_G$ greater than zero, indicating an increase in the actual residual AGB of grasslands during these years, mainly owing to better climatic conditions (Table 2). From 2000 to 2014, there were eight years of $sAGB_G$ less than zero, indicating a reduction in the actual residual grassland AGB. Climatic conditions became better in 2005, 2007, and 2013, but human activities (mainly grazing activities in the NTP) caused excessive use of the grassland, which exceeded its carrying capacity and caused a decrease in the grassland AGB_G. For the other five years of AGB_G reduction, deterioration of climatic conditions was the main reason for the decrease in grassland productivity.

Table 2
Causes for the aboveground biomass in the open grasslands (AGB_G) inter-annual variation.

Year	$sAGB_G$	$sAGB_F$	$sAGB_H$	Cause of AGB_G change
2001	2.12	5.13	3.00	ICC
2002	−1.18	−8.16	−6.98	DCC
2003	0.48	22.37	21.89	ICC
2004	−0.49	−25.73	−25.25	DCC
2005	−0.22	1.98	2.20	DHA
2006	−1.16	−13.37	−12.22	DCC
2007	−0.03	13.68	13.71	DHA
2008	1.17	29.33	28.16	ICC
2009	−0.38	−33.73	−33.35	DCC
2010	0.20	3.17	2.97	ICC
2011	1.52	15.68	14.16	ICC
2012	−0.48	−22.99	−22.51	DCC
2013	−1.25	6.43	7.68	DHA
2014	1.34	12.72	11.38	ICC

$sAGB_G$, $sAGB_F$, and $sAGB_H$ are the slope value for the aboveground biomass in the open grasslands (AGB_G), in the fenced grasslands (AGB_F), and induced by human (AGB_H) change trend.

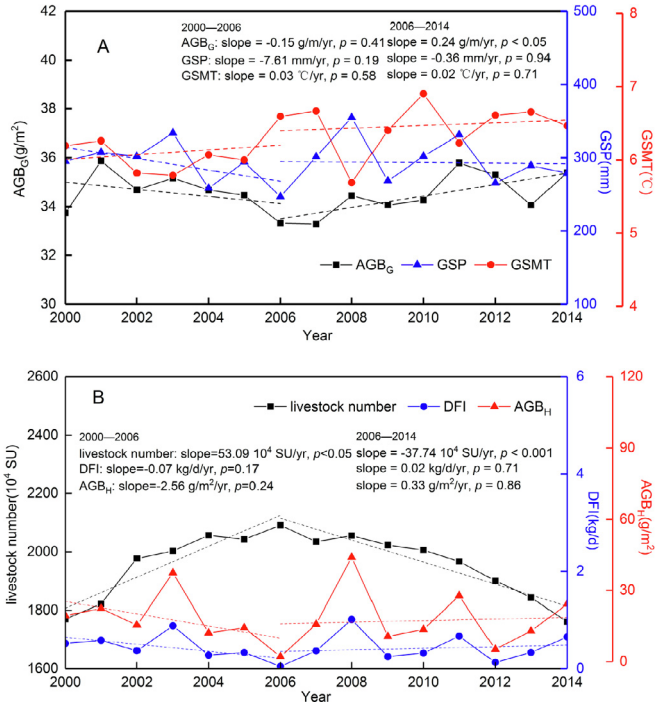

Fig. 5. Time series of (A) the aboveground biomass in the open grasslands (AGB_G), the growing season total precipitation (GSP), and the growing season average temperature (GSMT) and (B) the total livestock number, the aboveground biomass induced by human (AGB_H), and daily feed intake (DFI) of the Northern Tibetan Plateau from 2000 to 2014.

We choose two climatic factors: GSP and GSMT; three human factors: livestock number, daily feed intake (DFI) and AGB_H to further analyze the influence of climate change and human activities on AGB_G (Fig. 5). During the sub-period before 2006, the GSP of the NTP showed a downward trend with a decline rate of −7.61 mm/yr, and GSMT showed an upward trend with 0.03 °C/yr. Under the influence of warming and drying, AGB_G decreased. The downward trend of GSP has eased significantly during the second sub-period after 2006, and the growth rate of GSMT also slowed down. Due to better climatic conditions, AGB_G showed a significant upward trend. During the first sub-period, the number of livestock increased significantly, which affected the decrease of AGB_G. The number of livestock began to decrease significantly with -37.74×10^4 SU/yr in the second sub-period, which had a positive impact on the increase of AGB_G. DFI and AGB_H represent the consumption of AGB by livestock, but they have the same trend with AGB_G in these two sub-periods, indicating that these two factors have less influence on AGB_G changes. The influence factors are not completely independent of each other. In many cases, they work together and influence each other. We also found a significant positive correlation between GSP and AGB_H, which should be increased or decreased ($R^2 = 0.33$, $p < 0.05$). When the GSP is < 290 mm, the AGBH needs to be reduced and the grassland in an overgrazed state. When the GSP is > 290 mm, grassland resources are sufficient to increase AGB_H.

By comparing the absolute values of $sAGB_E$ and $sAGB_H$, we can obtain the spatial distribution of the causes of AGB_G changes for two sub-periods (Fig. 6). Between 2000 and 2006, the increase in AGB_G of the NTP was mainly owing to human activities. These regions were mainly located in the northern and central parts of the NTP (Fig. 6A). There were no regions where AGB_G increased owing to climate change, and there were no regions where AGB_G did not change. The regions with decreased AGB_G caused by human activities were mainly distributed in sporadic areas in the southwestern NTP (Fig. 6A). Areas where the AGB_G decreased owing to climate change were mainly distributed in southeastern NTP (Fig. 6A). The spatial distribution of

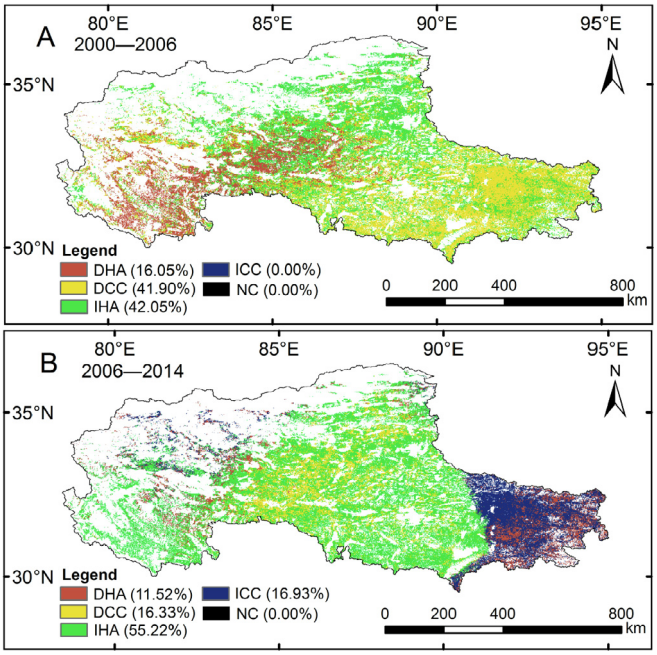

Fig. 6. Spatial distribution of causes for the aboveground biomass in the open grasslands (AGB_G) changes in the Northern Tibetan Plateau during the sub-periods of 2000–2006 (A) and 2006–2014 (B). Note: NC is AGB_G had no change; DHA is AGB_G decreased owing to human activities; DCC is AGB_G decreased owing to climate change; IHA is AGB_G increased owing to human activities, and ICC is AGB_G increased owing to climate change. In parentheses is the area percentages of AGB_G changes.

causes had changed from 2006 to 2014. The AGB_G increased in more regions, mostly caused by human activities, distributed in the southwestern, central, and southeastern NTP (Fig. 6B). The areas with increasing AGB_G owing to climate change were mainly distributed in the southeastern and northwestern NTP (Fig. 6B). The areas of decreased AGB_G caused by human activities were consistent with the areas of increased AGB_G caused by climate change, whereas the areas with decreased AGB_G caused by climate change were distributed in the central and southeastern NTP (Fig. 6B).

The area percentages of AGB_G changes, increasing or decreasing caused by climate or human factors were calculated for the two sub-periods 2000–2006 and 2006–2014 (Fig. 6). The results showed that the total area percentage of increased AGB_G increased from 42.05% to 72.15%, and the decreased AGB_G decreased from 57.95% to 27.85%. This indicates that the AGB_G of the grasslands on the NTP decreased during the first sub-period but was effectively restored in the second sub-period. The area of AGB_G changes caused by climate change decreased from 41.90% to 33.26%. Among them, the AGB_G increase owing to climate change increased from 0.00% to 16.93%, and the AGB_G decrease owing to climate change decreased from 41.90% to 16.33%. In the first sub-period, climate change was mainly negative to AGB_G. However, in the second sub-period, the negative effects of climate change decreased significantly and positive effects appeared. The area of AGB_G changes caused by human activities increased from 58.10% to 66.74%. Among them, the AGB_G increase due to human activities increased from 42.05% to 55.22%, and the AGB_G decrease due to human activities decreased from 16.05% to 11.52%. It shows that the changes in AGB_G in most areas of the NTP during these two sub-periods were caused by human activities. Reasonable arrangement of human activities was an effective means to promote the restoration of local grasslands, and this promotion was more pronounced in the second sub-period.

4. Discussion

The ecosystem of alpine grasslands on the NTP is very fragile and has sensitive responses to climate change (Gao et al., 2009; Zhang et al., 2007). From 2000 to 2014, climate change was the main reason for the change of AGB_G in the NTP. As the alpine grasslands on the NTP are mainly distributed in arid and semi-arid areas, they are vulnerable to precipitation and climate warming (Gao et al., 2016). During the first sub-period before 2006 , the warming and drying trend of the NTP has had a negative impact on AGB_G, making the grasslands more vulnerable to degradation. During the second sub-period , the climate conditions are improving , The slowing trend of drying and warming enabled the AGB_G of the NTP to recover effectively. Climate factors have a significant impact on the productivity of the alpine grasslands on the NTP; so, when using the grassland in the future, climatic conditions to conduct grazing activities should be monitored. As an important climate factor, GSP is of great significance to the growth of alpine grassland vegetation (Yan and Lu, 2015; Yang et al., 2009), and has a significant positive correlation with AGB_H that should be increased or decreased. When the value of AGB_H that should be increased or decreased is zero, the balance between forage production and livestock consumption can be reached. At this time, the value of GSP can be used as a warning in arranging grazing activities. Based on this, the number of livestock can be adjusted to use grassland resources more rationally.

Grazing activities are the main ways for humans to utilize alpine grasslands on the NTP. Excessive grazing activities are also responsible for grassland degradation (Wu et al., 2012). However, the relationship between livestock numbers and climate change and forage production is not well understood. Therefore, we selected the number of livestock, daily feed intake (DFI), and AGB_H to discuss the adaptability of livestock to environment and forage production. In 2000–2014, the change of AGB_H was consistent with the change of AGB_F. This certified that livestock consumption is adaptable to climate change and forage production. When weather conditions are good, AGB is relatively abundant, and livestock consumes more AGB. However, when climatic conditions are poor, AGB is relatively lacking, and livestock consumption also decreases. Between 2000 and 2014, the changes of AGB_H and livestock numbers showed opposite trends, and the changes of DFI and AGB_H were consistent. It can be seen that the number of livestock is not the decisive factor for AGB_H. Livestock will adapt to forage productivity through DFI, that is, more AGB_H years, more DFI for livestock, and fewer AGB_H years, lower DFI for livestock. This also shows that there is a problem with the traditional method of assessing the forage-livestock balance by using a fixed value of DFI. In years with lower DFI, if the number of livestock is not decreased, the growth of livestock may be affected, which requires providing supplementary feeds to ensure livestock growth. Livestock have some adaptability to environmental conditions and forage production, to ensure grassland is relatively stable (Chen et al., 2014). However, when the number of livestock is too high and supplements are inadequate, this stability will be broken and the grasslands will degenerate.

Owing to the implementation of the Grazing Withdrawal Program (GWP) policy and ecological compensation, the livestock number of NTP was effectively controlled (Yu et al., 2016). But the grasslands in parts of NTP were still overgrazed. Grazing activities should be arranged in space according to the actual situation of grasslands. The spatial distribution of the potential and pressure areas for future grazing activities can be obtained through the spatial distribution of AGB_H that should be increased or decreased in 2000–2014. We believe that the areas where the trend of AGB_G greater than zero are the potential areas for future grazing. In the past 15 years, the AGB in potential areas had a surplus; so, when planning grazing activities, focus should be on potential areas as much as possible. The areas where the trend of AGB_G less than zero are the pressure areas for future grazing. Grazing in pressure areas should be avoided to prevent aggravating grassland degradation in these areas. Since grazing activities are still the main ways

for human activities to utilize NTP grasslands, to realize the sustainable use of the grasslands, climatic conditions must be fully considered and grazing activities adjusted accordingly.

5. Conclusions

In the present study, we distinguished and quantified the impacts of climate change and human activities on the NTP, and dynamically assessed the NTP forage-livestock balance. Simultaneously, the causes of the spatial and temporal variations of AGB_G in the alpine grassland were determined. Overall, from 2000 to 2014, climate change was the main driving force of AGB_G in the alpine grasslands of NTP, and AGB_H was adaptable to the climate. Between 2000 and 2006, owing to poor climatic conditions, the AGB_G of the NTP showed a decreasing trend and most of the grasslands were in an overgrazed state. The number of livestock needed to be reduced to ensure the sustainable use of the grassland ecosystem. Between 2006 and 2014, climatic conditions improved, human activities became more rational, and AGB_G showed an increasing trend. Most of the grasslands were in surplus and the number of livestock could be increased appropriately. In the past 15 years, the AGB of the grasslands in the northern NTP had surpluses, which were potential areas for future grazing activities. In the southern and southeastern NTP, grasslands were over-utilized and pressure areas for grazing activities. Our research revealed that when determining future grazing activities climatic conditions should be considered and grazing activities adjusted accordingly. Furthermore, to assess the balance of forage production and livestock consumption more accurately, more field data is needed.

Author contributions

XZ designed the research. JW led the field surveys with the help of YC, BN, ML, YZ, XW, and ZW. YC collected the climate and remote sensing data, and performed the statistical analyses with the help of XZ and BN. YC led the writing. XZ, BN , and JW revised the text and interpreted the results. All authors contributed to this work and approved the final manuscript for publication. The authors declare that they have no competing interests.

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